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# Seismic Recording in Eastern California of the KEARSARGE Nuclear Test

JOHN CIPAR
CHARLES TAYLOR
JOSEPH CRAIG

6 November 1989



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John Cipar
Charles Taylor
Joseph Craig

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A temporary ten-station seismic network was operated in eastern California to record the KEARSARGE nuclear test at the Nevada Test Site. Data from 8 three-component, short-period stations and 2 three-component, mid-period stations are presented. Part of the array was arranged as a profile between 150 to 250 km from NTS. At these ranges, the first arrivals are Pn waves refracted along the crust-mantle boundary. The Pn travel times can be modeled by assuming a 32-km thick crust at NTS, which has a 3° westward dip beginning approximately 90 km west of the shot point. This model predicts a crustal thickness of 41.8 km at a point 277 km west of the shot point (that is, under the central Sierra Nevada). This model is in good agreement with the models of Eaton and of Pakiser and Brune and contrary to the model of Carder et al and Carder. There still remain significant offsets in the Carder et al NTS travel-time data in the 250 to 270 km and 360 to 390 km distance ranges. Closely-spaced, digitally-recorded observations in those distance ranges are needed to completely resolve the seismic structure of the Sierra Nevada-Basin and Range transition zone. Keywords:

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# Preface

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# Seismic Recording in Eastern California of the KEARSARGE Nuclear Test

## 1. KEARSARGE NUCLEAR TEST

The Joint Verification Experiment (JVE) between the United Sates and the Soviet Union involved two nuclear tests: KEARSARGE, detonated at the Nevada Test Site (NTS) on 17 August 1988, and SHAGAN, fired at the Soviet East Kazakh test area on 14 September 1988. Seismic measurements for both explosions were recorded by the Earth Sciences Division of the Geophysics Laboratory (GL) in conjunction with the Civil Engineering Research Division of the Weapons Laboratory (WL). Analysis of the SHAGAN seismograms recorded in the northeastern United States can be found in Cipar and Battis (in preparation).

This report describes the GL data obtained from KEARSARGE at stations in the Sierra Nevada Mountains and Owens Valley of eastern California. The goals of the GL KEARSARGE experiment were to determine the seismic radiation pattern of this underground nuclear test, and to measure crustal structure across the Basin and Range-Sierra Nevada transition zone.

While seismic radiation from an underground nuclear explosion is predominately isotropic, numerous observations suggest that several other processes are at work during or

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immediately after the detonation. Among these processes are tectonic release,[1,2,3] spall slapdown[4] and cavity collapse.[1] Any fully successful seismic source model must explain such observations as:[1]

1. azimuthal variation of Rayleigh wave amplitudes[5]
2. reversal in observed Rayleigh wave phase
3. enhanced horizontally-polarized shear and Love waves[6]
4. distortions of regional and teleseismic body waves.[7]

One of the goals of this experiment is to fill in part of the KEARSARGE radiation pattern not covered by existing stations. Particularly interesting is the comparison between KEARSARGE and regional data collected for the 6 June 1981 HARZER explosion.[4] KEARSARGE was detonated approximately 2 km from HARZER and the two explosions are comparable in size ($M_b$ determinations are 5.6 and 5.4 for HARZER and KEARSARGE, respectively). Patton[4] demonstrated the usefulness of higher-mode surface wave data to isolate the explosion moment for HARZER from second-order components of the moment tensor (for example, tectonic release), and explicitly included spall in his estimates of higher-mode amplitudes.

The crustal structure of the Sierra Nevada Mountains has been debated off-and-on for over 50 years (see Pakiser and Brune[8] for a review of earlier work). The bulk of the evidence indicates that the Sierras have a crustal root extending to 55 km beneath Mt. Whitney, while

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1 Masse, Robert P. (1981) Review of seismic source models for underground nuclear explosions, *Bull. Seism. Soc. Am.*, **71**, (No. 4):1249-1268.

2 Wallace, Terry C., Helmberger, Donald V., and Engen, Gladys R. (1983) Evidence of tectonic release from underground nuclear explosions in long-period P waves, *Bull. Seism. Soc. Am.*, **73**, (No. 2):593-613.

3 Wallace, Terry C., Helmberger, Donald V., and Engen, Gladys R. (1985) Evidence of tectonic release from underground nuclear explosions in long-period S waves, *Bull. Seism. Soc. Am.*, **75**, (No. 1):157-174.

4 Patton, Howard J. (1988) Source models of the HARZER explosion from regional observations of fundamental-mode and higher-mode surface waves, *Bull. Seism. Soc. Am.*, **78**, (No. 3):1133-1157.

5 Toksoz, M. Nafi and Kehrer, Harold H. (1972) Tectonic strain release by underground nuclear explosions and its effect on seismic discrimination, *Geophys. J. Roy. Astron. Soc.*, **31**, (No. 1-3):141-161.

6 Toksoz, M. Nafi, Thomson, Ker C., and Ahrens, Thomas J. (1971) Generation of seismic waves by explosions in prestressed media, *Bull. Seism. Soc. Am.*, **61**, (No.6):1589-1623.

7 Wallace, Terry C., Holt, William E., and Junkyoung, Kim (1987) *Effects of Tectonic Release on Broadband Regional Distance Body Waves*, AFGL-TR-87-0239, ADA194247.

8 Pakiser, L.C. and Brune, James N. (1980) Seismic models of the root of the Sierra Nevada, *Science*, **210**, (No. 4474):1088-1094.

the crustal thickness in the Basin and Range Province to the east is 35 km or less.[9, 10, 11, 12, 13] Carder et al[14] and Carder[15] challenge the existence of this root based on relatively sparse seismic data from nuclear explosions at the Nevada Test Site and California earthquakes. The stations installed by GL for the KEARSARGE experiment form a roughly east-west profile 155 to 250 km west of the Nevada Test Site. The profile samples waves propagating through the tectonically active region between the Sierra Nevada and Basin and Range Provinces. In a later section, we will discuss implications of the travel-time measurements for the existence of a Sierra crustal root.

## 2. OWENS VALLEY SEISMIC ARRAY

Ten stations were deployed in the eastern Sierra Nevada, across Owens Valley, and in the western Inyo-White Mountains (Figure 1). All location and elevation data were obtained from United States Geological Survey 15-min topographic maps and are listed in Table 1 along with pertinent information on the KEARSARGE shot. Each station consisted of a three-component seismometer set, a Terra Technology DCS-302 digital seismic recorder, and a WWVB radio time-code receiver.

---

9 Eaton, Jerry P. (1963) Crustal structure from San Francisco, California, to Eureka, Nevada, from seismic-refraction measurements, *Jour. Geophys. Res.*, **68**, (No. 20):5789-5806.

10 Johnson, Lane R. (1965) Crustal structure between Lake Mead, Nevada, and Mono Lake, California, *Jour. Geophys. Res.*, **70**, (No. 12):2863-2872.

11 Prodehl, Claus (1979) Crustal structure of the Western United States, *USGS Professional Paper* **1034**:74p.

12 Priestley, Keith, Orcutt, John A., and Brune, James N. (1980) Higher-mode surface waves and structure of the Great Basin of Nevada and Western Utah, *Jour. Geophys. Res.*, **85**, (No. B12):7166-7174.

13 Taylor, Steven R. (1983) Three-dimensional crust and upper mantle structure at the Nevada Test Site, *Jour. Geophys. Res.*, **88**, (No. B3):2220-2232.

14 Carder, D.S., Qamar, Anthony, and McEvilly, T.V. (1970) Trans-California seismic profile-Pahute Mesa to San Francisco Bay, *Bull. Seism. Soc. Am.*, **60**, (No. 6):1829-1846.

15 Carder, Dean S. (1973) Trans-California seismic profile, Death Valley to Monterey Bay, *Bull. Seism. Soc. Am.*, **63**, (No. 2):571-586.

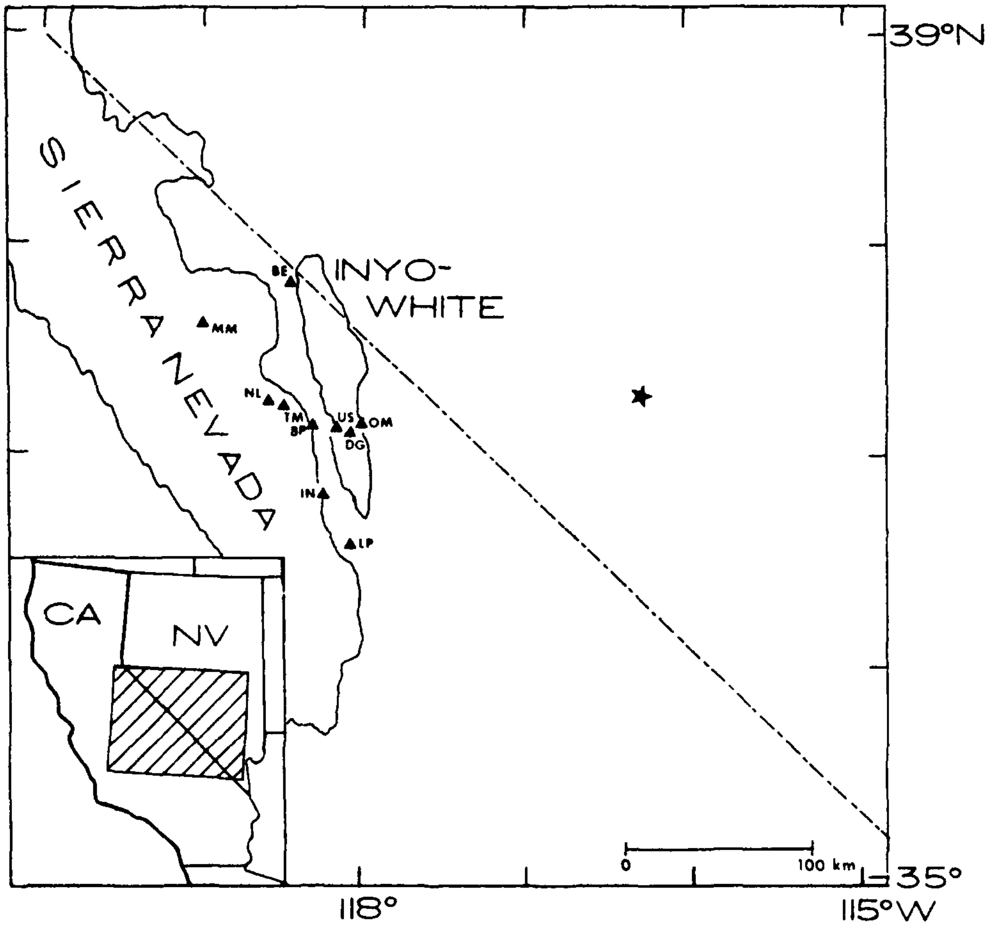


**Figure 1. Index Map of Eastern California - Western Nevada Showing the Location of the KEARSARGE Test (star) and Stations (triangles).**

Sprengnether S-6000 2-Hz triaxial seismometers were installed at North Lake (NLCA), Table Mountain (TMCA), and Big Pine (BPCA). Kinemetrics SH-1/SV-1 5-second seismometers were installed at Mammoth (MMCA) and Independence (INCA). The other stations - Benton (BECA), Ulymeyer Spring (USCA), Devil's Gate (DGCA), Overholtz Mine (OMCA), and Lone Pine (LPCA) had Hall-Sears HS-10-1B 1-Hz seismometers. The short-period seismometers were buried in shallow holes to minimize wind noise. The intermediate-period instruments at Mammoth (MMCA) were installed on an aluminum base plate and covered by a plywood box. At Independence, the intermediate-period sensors were placed in a ground-level storage cellar, again using the base plate. No appreciable drift was apparent during the week-long operation of the 5-second instruments. The horizontal components were aligned with respect to magnetic North. All sensor orientations are listed in Table 2. HS-10-1B and SV-1/SH-1 sensors were aligned using an aluminum base plate that was engraved with a North axis and

## Table 1. KEARSARGE Station Data

| Date | Origin Time | Latitude | Longitude | Depth | Elevation | Location |
|---|---|---|---|---|---|---|
| August 17, 1988 | 230d 17h 0m 0.095s | 37.297N | 116.307W | 0.615 | 1400.0 | Kearsarge, Nevada Test Site |

| Station | | Latitude (Deg) | Longitude (Deg) | Elevation (Meters) | Delta (Deg) | Distance (Km) | Azimuth (Deg) | Back Azimuth (Deg) | Location |
|---|---|---|---|---|---|---|---|---|---|
| MMCA | AFGL | 37.630N | 118.901W | 2468.76 | 2.103 | 240.43 | 270.88 | 08.25 | Mammoth, California |
| BECA | AFGL | 37.860N | 118.453W | 1737.28 | 1.795 | 190.02 | 288.88 | 107.57 | Benton, California |
| NLCA | AFGL | 37.231N | 118.618W | 2852.79 | 1.846 | 205.19 | 268.65 | 87.25 | North Lake, California |
| TMCA | AFGL | 37.209N | 118.568W | 2682.11 | 1.807 | 200.88 | 267.00 | 86.53 | Table Mountain Camp, California |
| BPCA | AFGL | 37.150N | 118.327W | 1414.20 | 1.620 | 180.08 | 265.40 | 84.18 | Big Pine, California |
| USCA | AFGL | 37.183N | 118.219W | 1310.58 | 1.530 | 170.14 | 266.30 | 85.14 | Ulymeyer Spring, California |
| DXCA | AFGL | 37.143N | 118.121W | 1001.80 | 1.457 | 161.08 | 264.48 | 83.38 | Devil's Gate, California |
| OMCA | AFGL | 37.144N | 118.049W | 2340.75 | 1.399 | 155.57 | 264.23 | 83.18 | Overholtz Mine Road, California |
| INCA | AFGL | 36.832N | 118.244W | 1304.48 | 1.618 | 179.94 | 253.80 | 72.73 | Independence, California |
| LPCA | AFGL | 36.558N | 118.148W | 1200.80 | 1.652 | 183.71 | 243.81 | 68.70 | Lone Pine, California |

## Table 2. Seismometer Constants

| Seismogram | Starting Time Date | d | h | m | s | Time Correction (Seconds) | | Seismometer Orientation (Degrees) | Seismometer Sensitivity (Volts/m/sec) | Pendulum Period (Seconds) | Damping Ratio | Serial Number | Calibration Date | Polar -ity |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MMCA KEAR MPN | 17 AUG 1988 | 230 | 17 | 0 | 28.000 | -0.0234 | WWVB | 18.20 | 290.9156 | 5.537 | 0.965 | 231 | 14 AUG 1988 | 1 |
| MMCA KEAR MPE | 17 AUG 1988 | 230 | 17 | 0 | 28.000 | -0.0234 | WWVB | 108.20 | 125.9160 | 4.965 | 0.835 | 236 | 14 AUG 1988 | 1 |
| MMCA KEAR MPZ | 17 AUG 1988 | 230 | 17 | 0 | 28.000 | 0.0234 | WWVB | | 98.8847 | 5.005 | 0.816 | 160 | 14 AUG 1988 | 1 |
| BECA KEAR SPN | 17 AUG 1988 | 230 | 17 | 0 | 33.150 | 2.4207 | WWVB | 18.20 | 686.5820 | 0.664 | 1.037 | 104545 | 11 AUG 1988 | 1 |
| BECA KEAR SPE | 17 AUG 1988 | 230 | 17 | 0 | 33.150 | 2.4207 | WWVB | 108.20 | 694.8103 | 0.797 | 1.026 | 104546 | 11 AUG 1988 | 1 |
| BECA KEAR SPZ | 17 AUG 1988 | 230 | 17 | 0 | 33.150 | 2.4207 | WWVB | | 695.6477 | 1.002 | 1.245 | 104552 | 11 AUG 1988 | 1 |
| NLCA KEAR SPN | 17 AUG 1988 | 230 | 17 | 0 | 23.000 | 0.7541 | WWVB | 16.20 | 92.0440 | 0.471 | 0.365 | 9337 | 17 AUG 1988 | 1 |
| NLCA KEAR SPE | 17 AUG 1988 | 230 | 17 | 0 | 23.000 | 0.7541 | WWVB | 106.20 | 96.9418 | 0.504 | 0.417 | 9337 | 17 AUG 1988 | 1 |
| NLCA KEAR SPZ | 17 AUG 1988 | 230 | 17 | 0 | 23.000 | 0.7541 | WWVB | - | 106.1902 | 0.385 | 0.351 | 9337 | 17 AUG 1988 | 1 |
| TMCA KEAR SPN | 17 AUG 1988 | 230 | 17 | 0 | 27.230 | 0.0000 | WWVB | 18.00 | 117.5801 | 0.489 | 0.411 | 9325 | 17 AUG 1988 | 1 |
| TMCA KEAR SPE | 17 AUG 1988 | 230 | 17 | 0 | 27.230 | 0.0000 | WWVB | 108.00 | 110.3007 | 0.484 | 0.487 | 9325 | 17 AUG 1988 | 1 |
| TMCA KEAR SPZ | 17 AUG 1988 | 230 | 17 | 0 | 27.230 | 0.0000 | WWVB | | 105.6600 | 0.420 | 0.334 | 9325 | 17 AUG 1988 | 1 |
| BPCA KEAR SPN | 17 AUG 1988 | 230 | 17 | 0 | 27.810 | 0.0078 | WWVB | 17.30 | 90.3205 | 0.500 | 0.424 | 9322 | 16 AUG 1988 | 1 |
| BPCA KEAR SPE | 17 AUG 1988 | 230 | 17 | 0 | 27.810 | 0.0078 | WWVB | 107.30 | 92.5480 | 0.406 | 0.301 | 9322 | 16 AUG 1988 | 1 |
| BPCA KEAR SPZ | 17 AUG 1988 | 230 | 17 | 0 | 27.810 | 0.0078 | WWVB | | 79.5186 | 0.373 | 0.296 | 9322 | 16 AUG 1988 | 1 |
| USCA KEAR SPN | 17 AUG 1988 | 230 | 17 | 0 | 27.960 | 0.1016 | WWVB | 17.30 | 794.2493 | 1.007 | 1.190 | 104543 | 13 AUG 1988 | 1 |
| USCA KEAR SPE | 17 AUG 1988 | 230 | 17 | 0 | 27.960 | 0.1016 | WWVB | 107.30 | 757.9926 | 0.637 | 0.811 | 104544 | 13 AUG 1988 | 1 |
| USCA KEAR SPZ | 17 AUG 1988 | 230 | 17 | 0 | 27.960 | 0.1016 | WWVB | | 634.4429 | 0.988 | 1.214 | 104555 | 13 AUG 1988 | 1 |
| DGCA KEAR SPN | 17 AUG 1988 | 230 | 17 | 0 | 25.880 | 0.0353 | GOES | 17.30 | 503.0849 | 1.069 | 1.596 | 104371 | 14 AUG 1988 | 1 |
| DGCA KEAR SPE | 17 AUG 1988 | 230 | 17 | 0 | 25.880 | 0.0353 | GOES | 107.30 | 465.6530 | 0.973 | 1.559 | 104372 | 14 AUG 1988 | 1 |
| DGCA KEAR SPZ | 17 AUG 1988 | 230 | 17 | 0 | 25.880 | 0.0353 | GOES | | 586.4774 | 0.958 | 1.492 | 104370 | 14 AUG 1988 | 1 |
| OMCA KEAR SPN | 17 AUG 1988 | 230 | 17 | 0 | 22.310 | 0.4063 | WWVB | 17.30 | 211.4146 | 0.896 | 1.097 | 104702 | 14 AUG 1988 | 1 |
| OMCA KEAR SPE | 17 AUG 1988 | 230 | 17 | 0 | 22.310 | 0.4063 | WWVB | 107.30 | 223.9243 | 0.829 | 1.003 | 104701 | 14 AUG 1988 | 1 |
| OMCA KEAR SPZ | 17 AUG 1988 | 230 | 17 | 0 | 22.310 | 0.4063 | WWVB | - | 175.8516 | 0.710 | 0.870 | 104554 | 14 AUG 1988 | 1 |
| INCA KEAR MPN | 17 AUG 1988 | 230 | 17 | 0 | 20.000 | 0.6354 | GOES | 17.30 | 124.6123 | 4.929 | 0.795 | 248 | 17 AUG 1988 | 1 |
| INCA KEAR MPE | 17 AUG 1988 | 230 | 17 | 0 | 20.000 | 0.6354 | GOES | 107.30 | 178.5233 | 4.871 | 0.902 | 247 | 17 AUG 1988 | 1 |
| INCA KEAR MPZ | 17 AUG 1988 | 230 | 17 | 0 | 20.000 | 0.6354 | GOES | - | 265.5179 | 4.983 | 0.860 | 167 | 17 AUG 1988 | 1 |
| LPCA KEAR SPN | 17 AUG 1988 | 230 | 17 | 0 | 34.870 | 2.0630 | GOES | 17.20 | 722.5986 | 0.921 | 1.091 | 104540 | 12 AUG 1988 | 1 |
| LPCA KEAR SPE | 17 AUG 1988 | 230 | 17 | 0 | 34.870 | 2.0630 | GOES | 107.20 | 657.8917 | 1.000 | 1.199 | 104548 | 12 AUG 1988 | 1 |
| LPCA KEAR SPZ | 17 AUG 1988 | 230 | 17 | 0 | 34.870 | 2.0630 | GOES | - | 517.6428 | 0.620 | 0.736 | 104556 | 12 AUG 1988 | 1 |

Seismometer orientation is measured as degrees clockwise from geographic north

indentations for the seismometer leveling feet. The S-6000 sensors were oriented using the longitudinal axis arrow engraved on the case. In all cases, the sensors were aligned within 5° of the orientation to the Earth's magnetic axes.

The DCS-302 recorders employ cassette tapes to hold approximately 13 minutes of three-channel data. Recorder response is flat from DC to the 30-Hz anti-aliasing filter cutoff frequency. Above the cutoff frequency, the response rolls off at 6 dB/octave using a five-pole Butterworth filter. The recorders use a 12-bit data word and automatic gain ranging over four gain settings to provide 126 dB of dynamic range. At a given gain, recorder sensitivity is given by 5.0 volts/2048 counts/gain. Gain values are nominally 10, 50, 250, and 1000. Specific values for each recorder at each gain are given in Table 3.

Stations were calibrated by driving the seismometer calibration coil with a measured current and recording the output pulse of the main coil through the recorder onto cassette tape. Thus, the calibration pulse represents the complete system (seismometer plus recorder) response. Seismometer constants are determined by fitting the observed amplitude spectrum

Table 3. Recorder Constraints

| Seismogram | Cut-off Frequency (Hertz) | Recorder Gains (Millivolts/Count) Gain 1 | Gain 2 | Gain 3 | Gain 4 | Serial Number |
|---|---|---|---|---|---|---|
| MMCA KEAR MPN | 30.00 | 0.24294 | 0.04881 | 0.00965 | 0.00239 | 279 |
| MMCA KEAR MPE | 30.00 | 0.24398 | 0.04909 | 0.00970 | 0.00241 | 279 |
| MMCA KEAR MPZ | 30.00 | 0.24353 | 0.04899 | 0.00967 | 0.00240 | 279 |
| BECA KEAR SPN | 30.00 | 0.23894 | 0.05039 | 0.00974 | 0.00238 | 277 |
| BECA KEAR SPE | 30.00 | 0.23851 | 0.04903 | 0.00964 | 0.00246 | 277 |
| BECA KEAR SPZ | 30.00 | 0.23872 | 0.04906 | 0.00971 | 0.00246 | 277 |
| NLCA KEAR SPN | 30.00 | 0.24414 | 0.04883 | 0.00977 | 0.00244 | 337 |
| NLCA KEAR SPE | 30.00 | 0.24414 | 0.04883 | 0.00977 | 0.00244 | 337 |
| NLCA KEAR SPZ | 30.00 | 0.24414 | 0.04883 | 0.00977 | 0.00244 | 337 |
| TMCA KEAR SPN | 30.00 | 0.24414 | 0.04833 | 0.00977 | 0.00244 | 260 |
| TMCA KEAR SPE | 30.00 | 0.24414 | 0.04883 | 0.00977 | 0.00244 | 260 |
| TMCA KEAR SPZ | 30.00 | 0.24414 | 0.04883 | 0.00977 | 0.00244 | 260 |
| BPCA KEAR SPN | 30.00 | 0.24414 | 0.04883 | 0.00977 | 0.00244 | 336 |
| BPCA KEAR SPE | 30.00 | 0.24414 | 0.04883 | 0.00977 | 0.00244 | 336 |
| BPCA KEAR SPZ | 30.00 | 0.24414 | 0.04883 | 0.00977 | 0.00244 | 336 |
| USCA KEAR SPN | 30.00 | 0.25006 | 0.04931 | 0.00978 | 0.00250 | 282 |
| USCA KEAR SPE | 30.00 | 0.25006 | 0.04927 | 0.00973 | 0.00240 | 282 |
| USCA KEAR SPZ | 30.00 | 0.25006 | 0.04902 | 0.00971 | 0.00249 | 282 |
| DGCA KEAR SPN | 30.00 | 0.24396 | 0.04964 | 0.00974 | 0.00240 | 312 |
| DGCA KEAR SPE | 30.00 | 0.24396 | 0.04884 | 0.00987 | 0.00245 | 312 |
| DGCA KEAR SPZ | 30.00 | 0.24374 | 0.04893 | 0.00982 | 0.00239 | 312 |
| OMCA KEAR SPN | 30.00 | 0.25326 | 0.04907 | 0.00970 | 0.00245 | 334 |
| OMCA KEAR SPE | 30.00 | 0.25511 | 0.04952 | 0.00980 | 0.00246 | 334 |
| OMCA KEAR SPZ | 30.00 | 0.25564 | 0.04973 | 0.00981 | 0.00242 | 334 |
| INCA KEAR MPN | 30.00 | 0.24414 | 0.04883 | 0.00977 | 0.00244 | 278 |
| INCA KEAR MPE | 30.00 | 0.24414 | 0.04883 | 0.00977 | 0.00244 | 278 |
| INCA KEAR MPZ | 30.00 | 0.24414 | 0.04883 | 0.00977 | 0.00244 | 278 |
| LPCA KEAR SPN | 30.00 | 0.24381 | 0.04926 | 0.00980 | 0.00244 | 320 |
| LPCA KEAR SPE | 30.00 | 0.24344 | 0.04917 | 0.00990 | 0.00246 | 320 |
| LPCA KEAR SPZ | 30.00 | 0.24381 | 0.04918 | 0.00983 | 0.00241 | 320 |

of the calibration pulse to the response of a damped pendulum filtered by the low-pass anti-aliasing filter.[16] Seismograph system constants (sensitivity, natural period, and damping) are given in Table 2. Recorder gain constants are measured independently (see Table 3).

Timing was accomplished in two ways. Prior to the experiment, the internal clock of each recorder was set to universal time (UTC) provided by a GOES satellite receiver. Clock drift was measured as soon as possible after the experiment by measuring the recorder slew, the number of digital sample intervals between the external time reference and the recorder internal clock. This drift can then be linearly interpolated to the event time to obtain the clock correction. Unfortunately, this method is ambiguous for clock drifts greater than one second. The preferred timing method is to measure the time correction using the WWVB radio time signal which is encoded continuously with the data. Table 2 lists the time corrections to be added to the seismogram starting times to get UTC. The "WWVB" or "GOES" after the time correction indicates which method was used in the correction.

The DCS-302 begins recording either by using an internal signal detection alorithm or by manual turn-on. Stations MMCA, NLCA, and INCA were switched manually. The other stations were triggered using a short-term/long-term average algorithm (STA/LTA) with STA = 1.0 sec, LTA = 20 sec, and the ratio = 10-12 dB. All stations triggered on the event and all apparently recorded the first arrival.

The built-in pre-event memory of approximately 4-sec is too short to record a useable noise sample before the event. It is not clear whether the recorders triggered on the small amplitude Pn phase or on the larger Pg phase that follows Pn by 3 to 4-sec at these ranges.

Significant problems surfaced in using DCS-302 intruments to record an event as large as KEARSARGE. Data recording stopped prematurely because, as the event came in, the LTA level rose so that even a large STA could not retrigger the recorder. A more serious problem was that the recorder gain ranging could not keep pace with the rapid rise in amplitude when the Pg phase arrived. Clearly a 16-bit recorder with long pre- and post-event memory could have alleviated the problems encountered during this deployment.

The first 18-sec of the KEARSARGE seismograms are shown in Figures 2-11, 60-sec of data for stations MMCA, NLCA and INCA are displayed in Figures 12-14. A common amplitude scale is used to facilitate comparison between records. Seismograms represent pendulum velocity, that is, they are not corrected for instrument response. Starting times are in UTC. Note the severe clipping on the OMCA seismogram; less severe clipping can be seen on the DGCA and USCA records.

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16 Mitchell, B.J. and Landisman, M. (1969) Electromagnetic seismograph constants by least squares inversion, *Bull. Seism. Soc. Am.*, **59**, (No. 3):1335-1348.

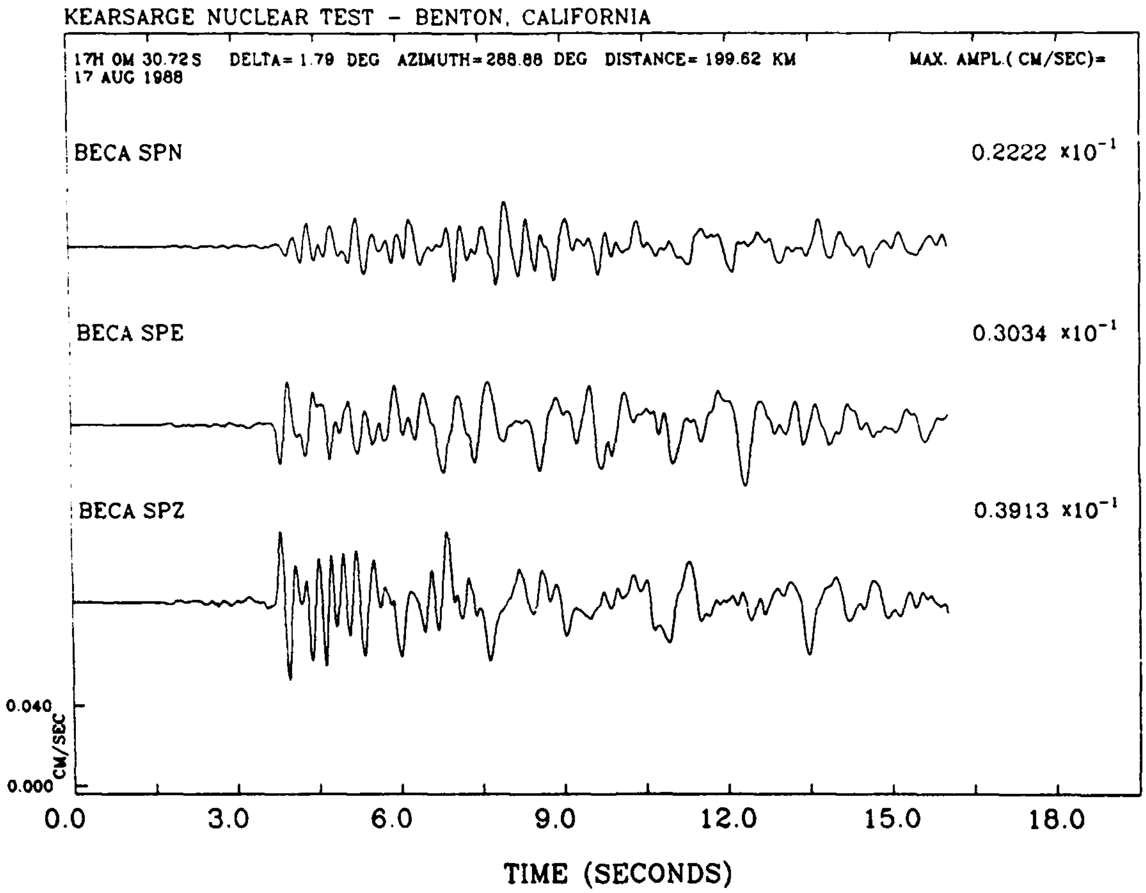


**Figure 2. Seismograms of the Pn and Pg Phases From the KEARSARGE Test Recorded at Benton, California. Each trace represents pendulum motion, uncorrected for instrument response. Absolute amplitude scale (shown at bottom left) in cm/sec is used. Distance, azimuth, and back azimuth are given at the top.**

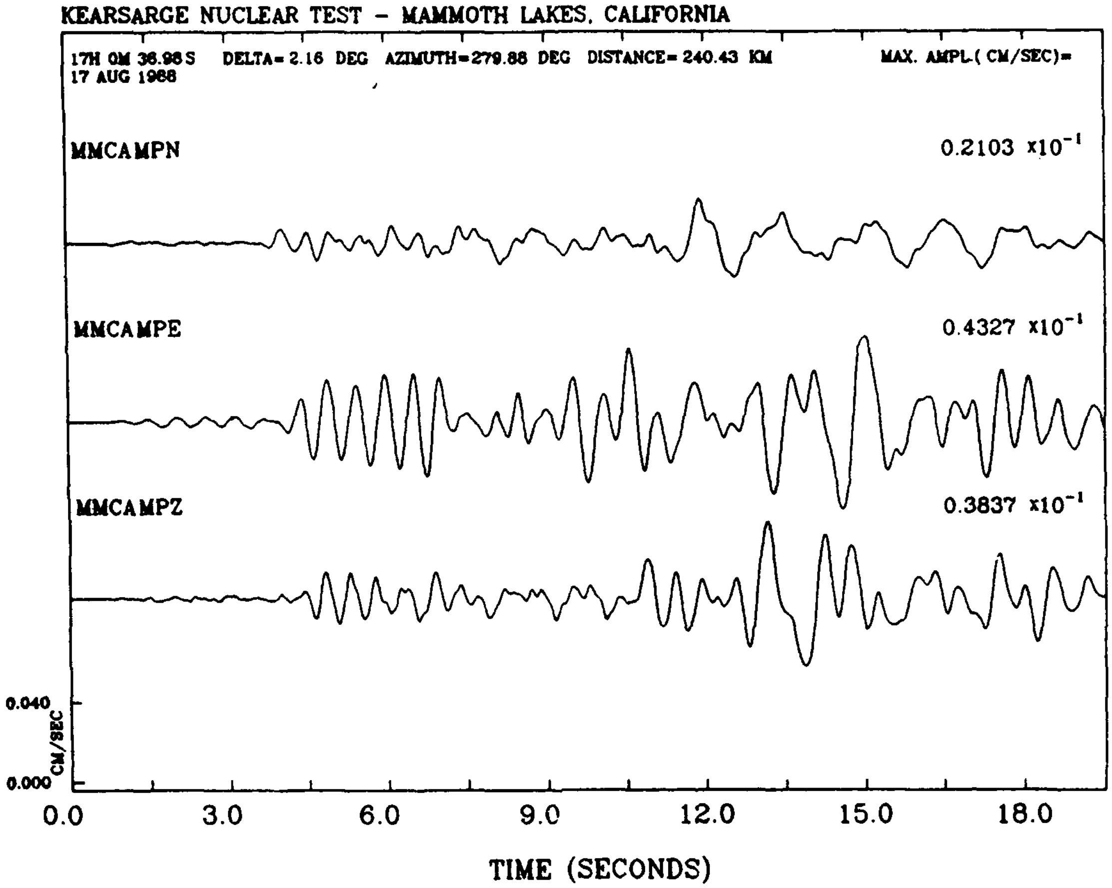


Figure 3. Seismograms of KEARSARGE Test Recorded at Mammoth Lakes, California. Each trace represents pendulum motion, uncorrected for instrument response. Absolute amplitude scale (shown at bottom left) in cm/sec is used. Distance, azimuth, and back azimuth are given at the top.

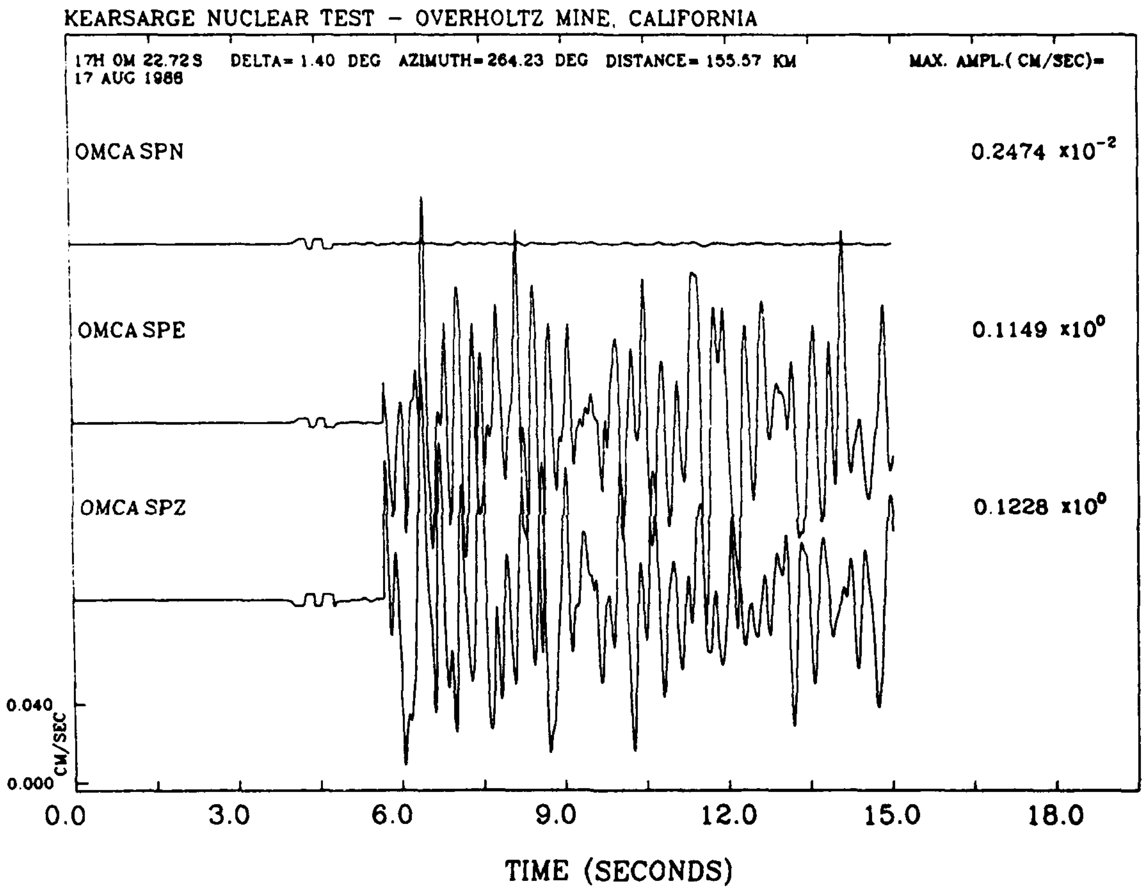


**Figure 4.** Seismograms of KEARSARGE Test Recorded at Overholtz Mine, California. Each trace represents pendulum motion, uncorrected for instrument response. Absolute amplitude scale (shown at bottom left) in cm/sec is used. Distance, azimuth, and back azimuth are given at the top.

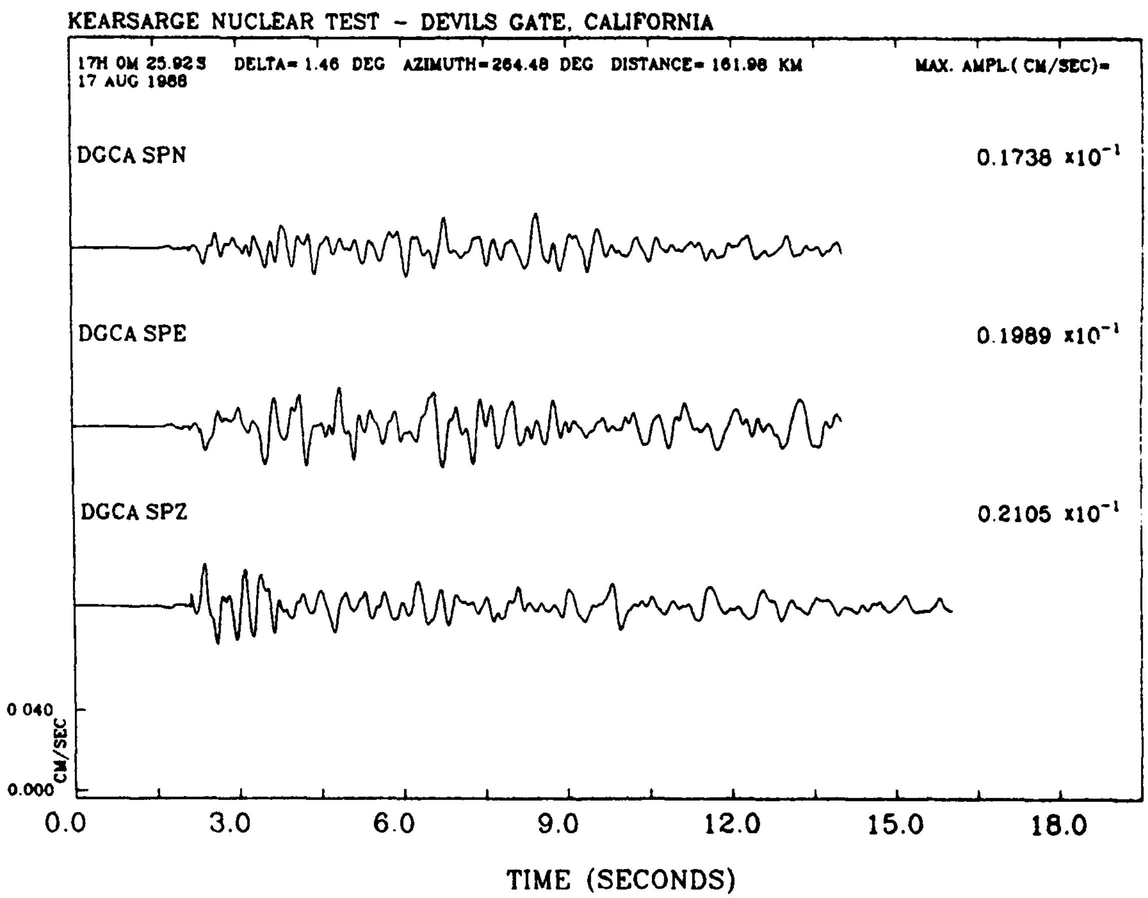


Figure 5. Seismograms of KEARSARGE Test Recorded at Devil's Gate, California. Each trace represents pendulum motion, uncorrected for instrument response. Absolute amplitude scale (shown at bottom left) in cm/sec is used. Distance, azimuth, and back azimuth are given at the top.

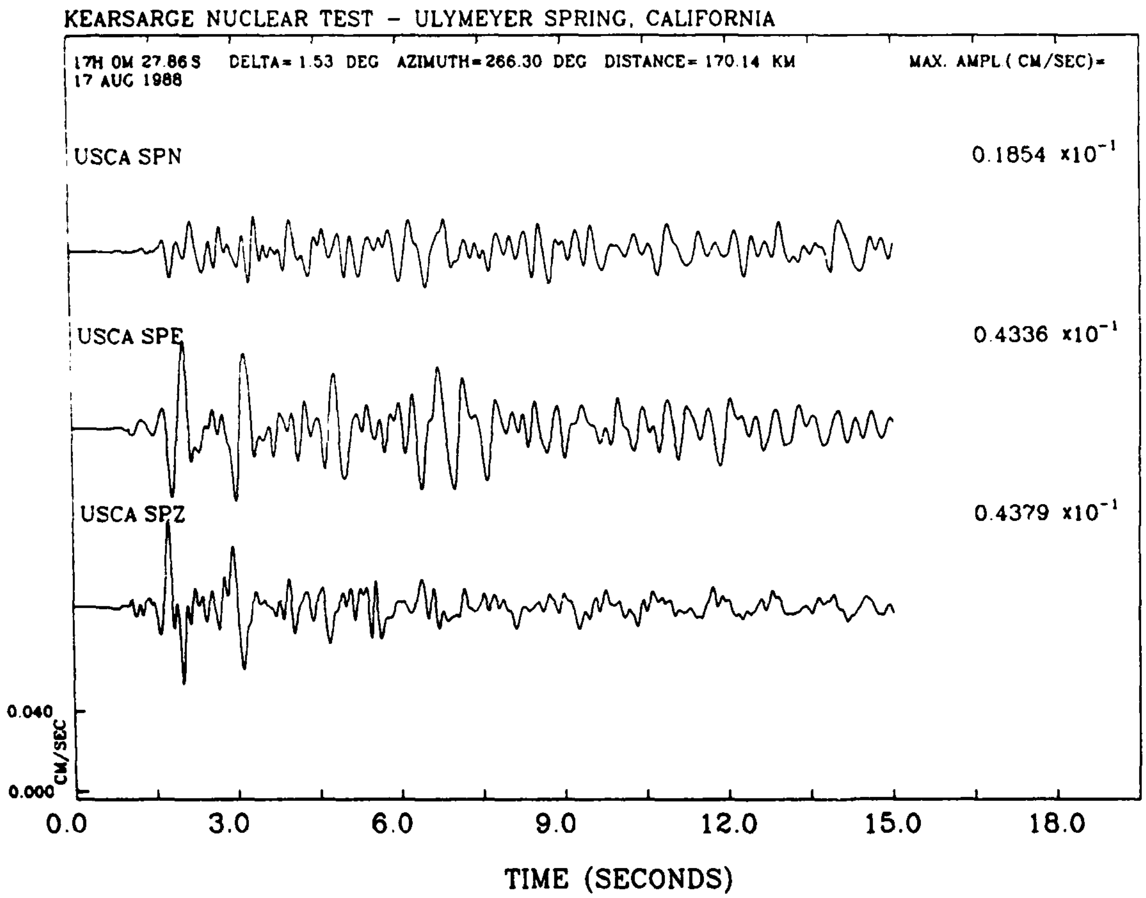


**Figure 6.** Seismograms of KEARSARGE Test Recorded at Ulymeyer Spring, California. Each trace represents pendulum motion, uncorrected for instrument response. Absolute amplitude scale (shown at bottom left) in cm/sec is used. Distance, azimuth, and back azimuth are given at the top.

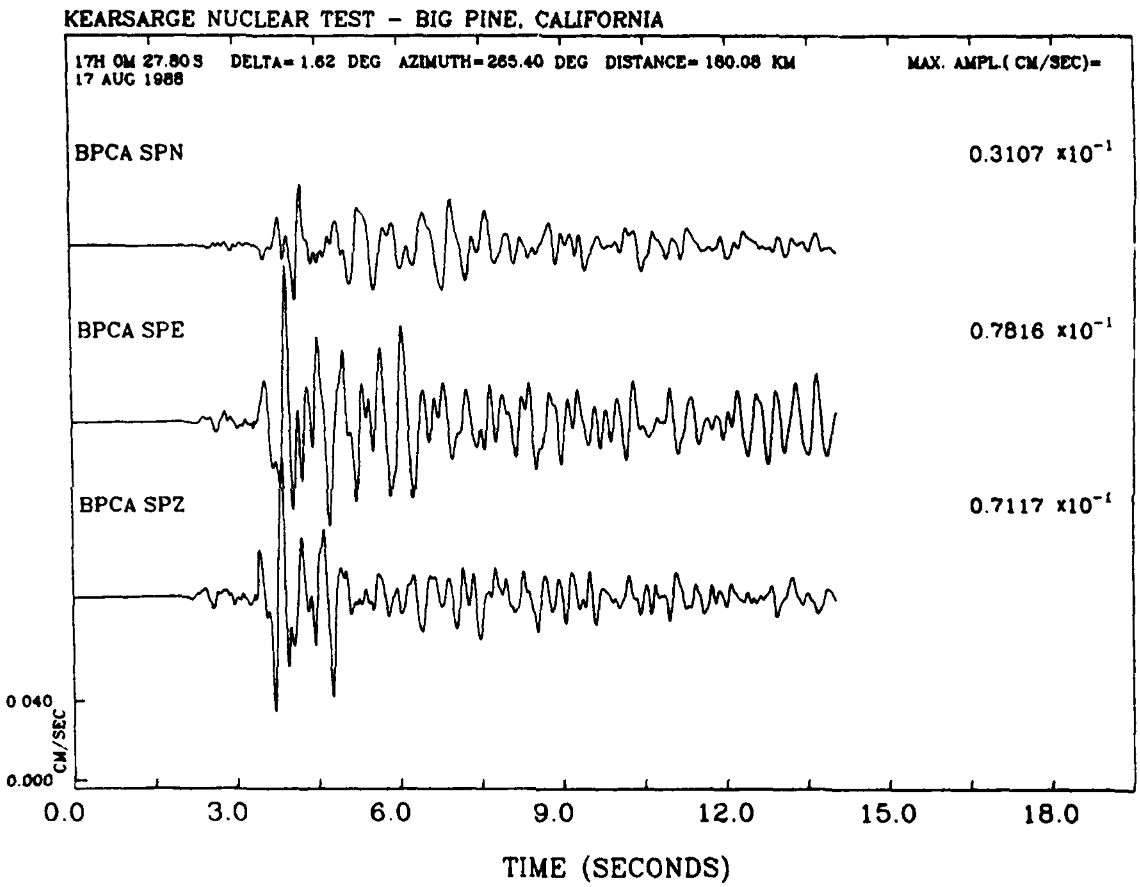


Figure 7. Seismograms of KEARSARGE Test Recorded at Big Pine, California. Each trace represents pendulum motion, uncorrected for instrument response. Absolute amplitude scale (shown at bottom left) in cm/sec is used. Distance, azimuth, and back azimuth are given at the top.

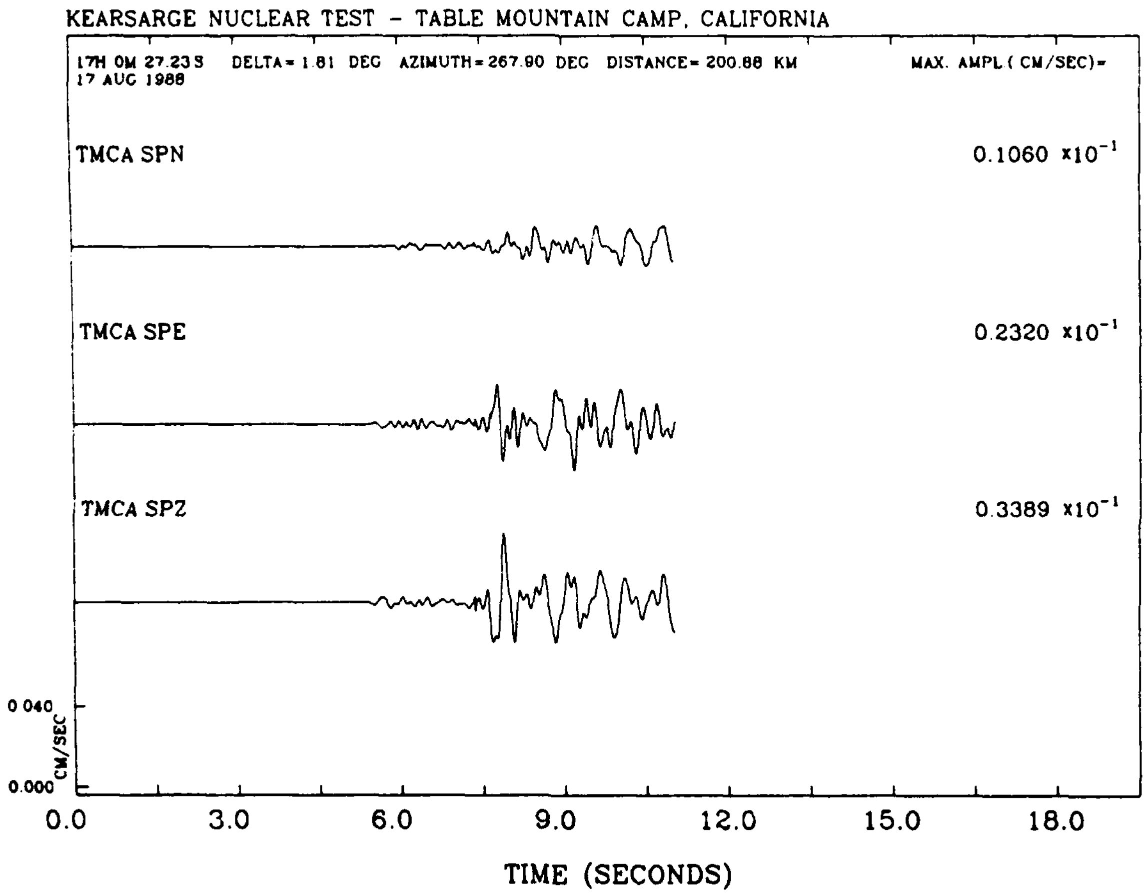


**Figure 8.** Seismograms of KEARSARGE Test Recorded at Table Mountain, California. Each trace represents pendulum motion, uncorrected for instrument response. Absolute amplitude scale (shown at bottom left) in cm/sec is used. Distance, azimuth, and back azimuth are given at the top.

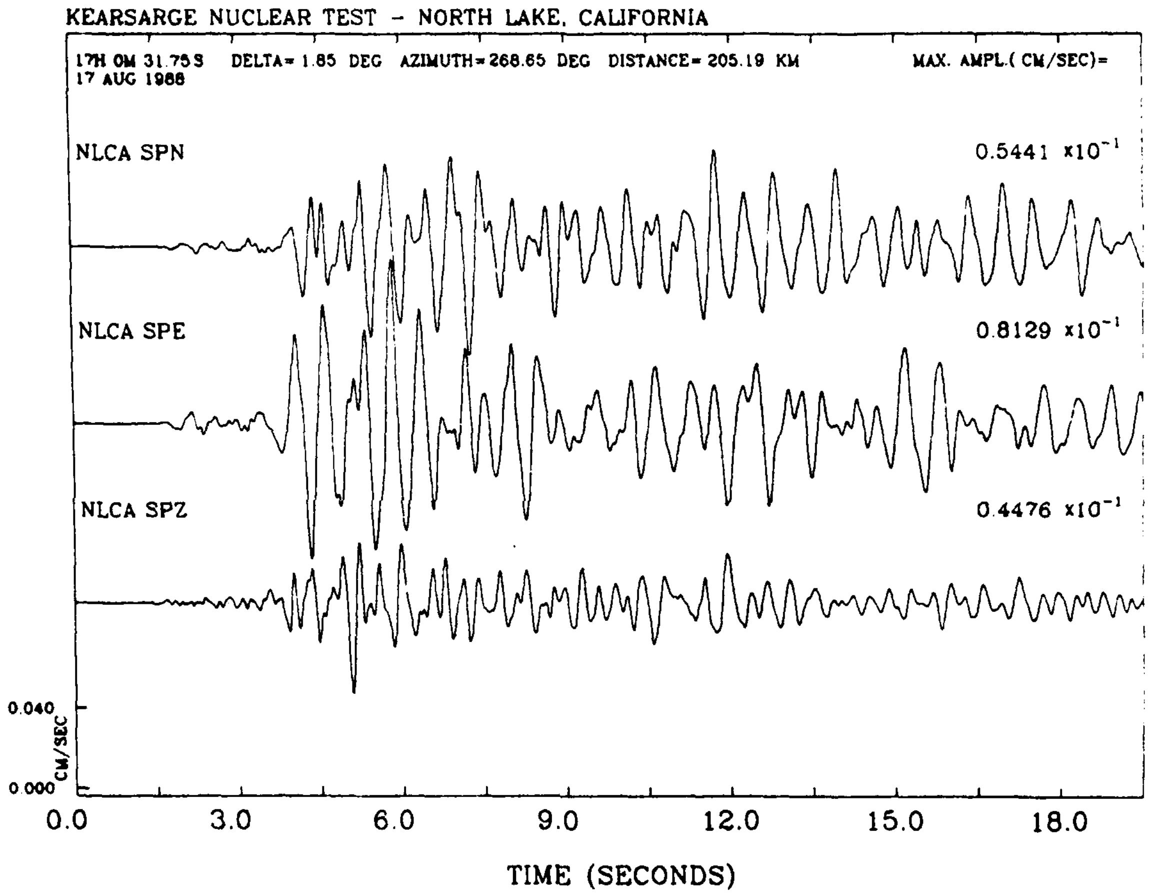


Figure 9. Seismograms of KEARSARGE Test Recorded at North Lake, California. Each trace represents pendulum motion, uncorrected for instrument response. Absolute amplitude scale (shown at bottom left) in cm/sec is used. Distance, azimuth, and back azimuth are given at the top.

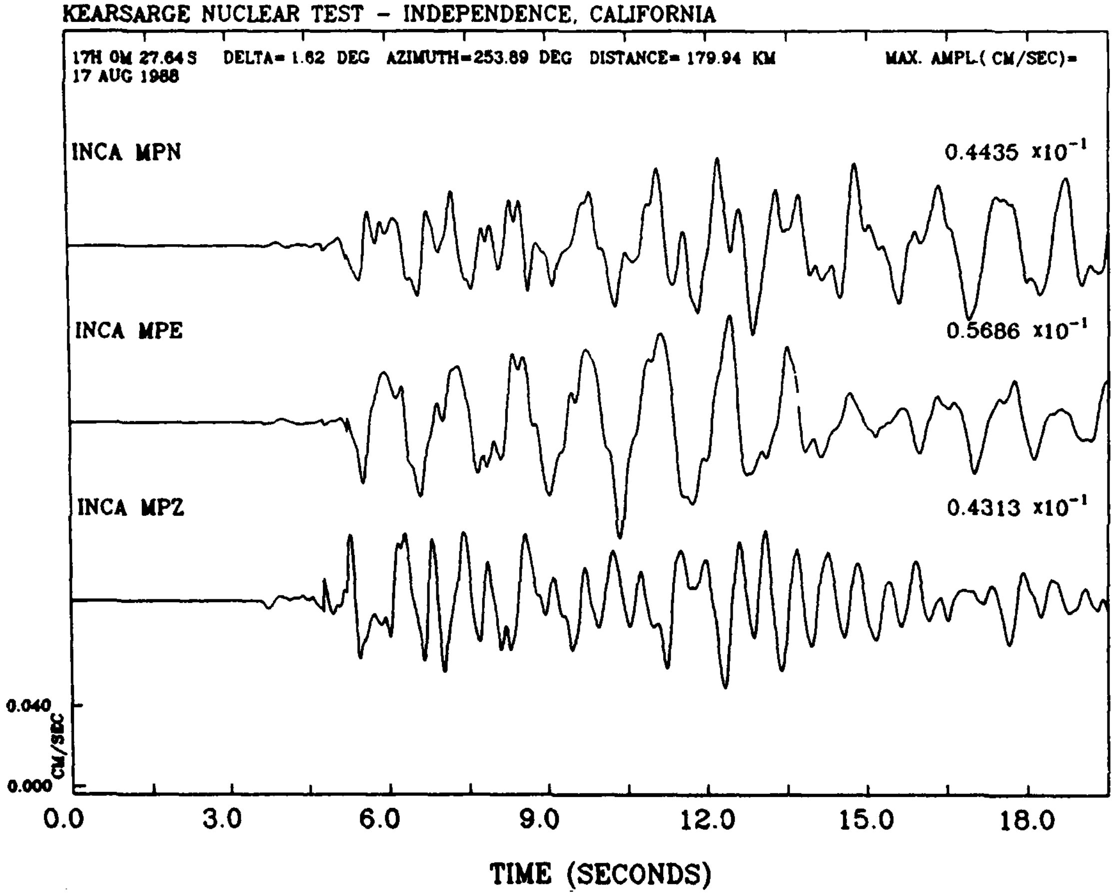


**Figure 10.** Seismograms of KEARSARGE Test Recorded at Independence, California. Each trace represents pendulum motion, uncorrected for instrument response. Absolute amplitude scale (shown at bottom left) in cm/sec is used. Distance, azimuth, and back azimuth are given at the top.

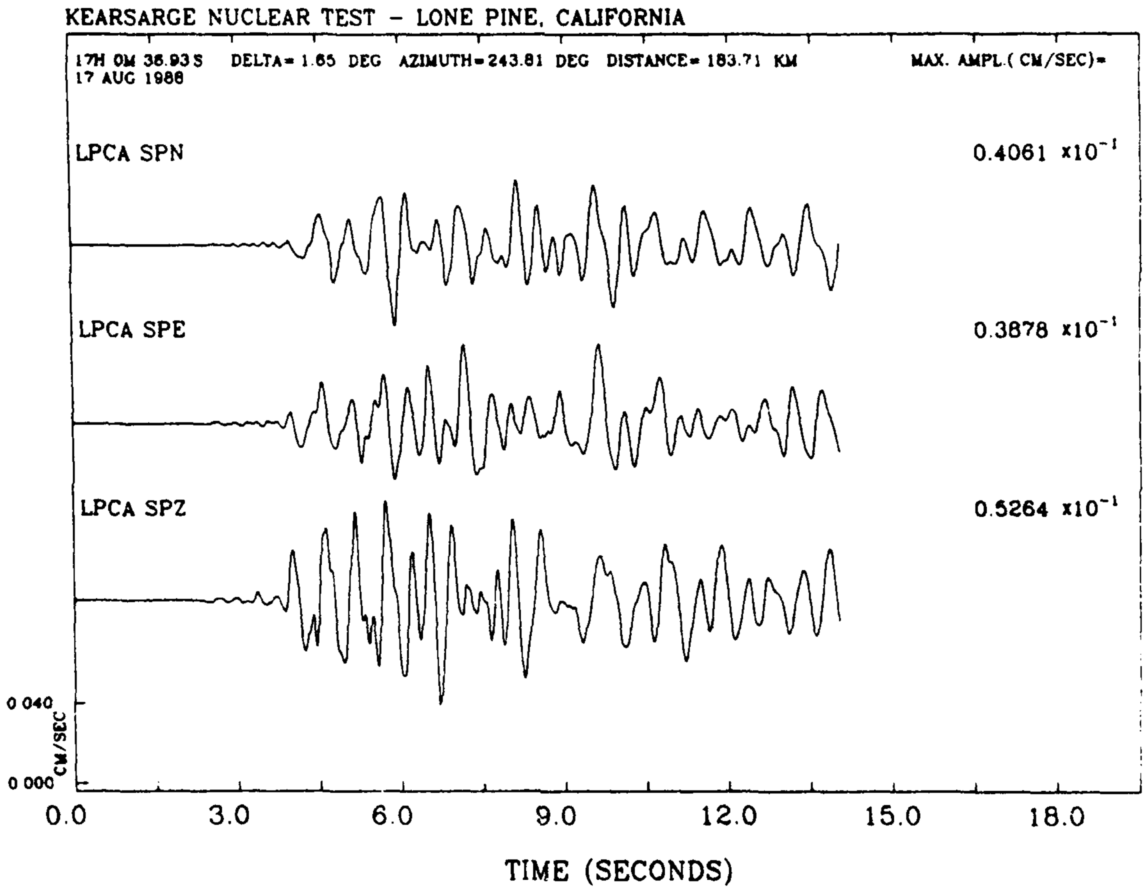


Figure 11. Seismograms of KEARSARGE Test Recorded at Lone Pine, California. Each trace represents pendulum motion, uncorrected for instrument response. Absolute amplitude scale (shown at bottom left) in cm/sec is used. Distance, azimuth, and back azimuth are given at the top.

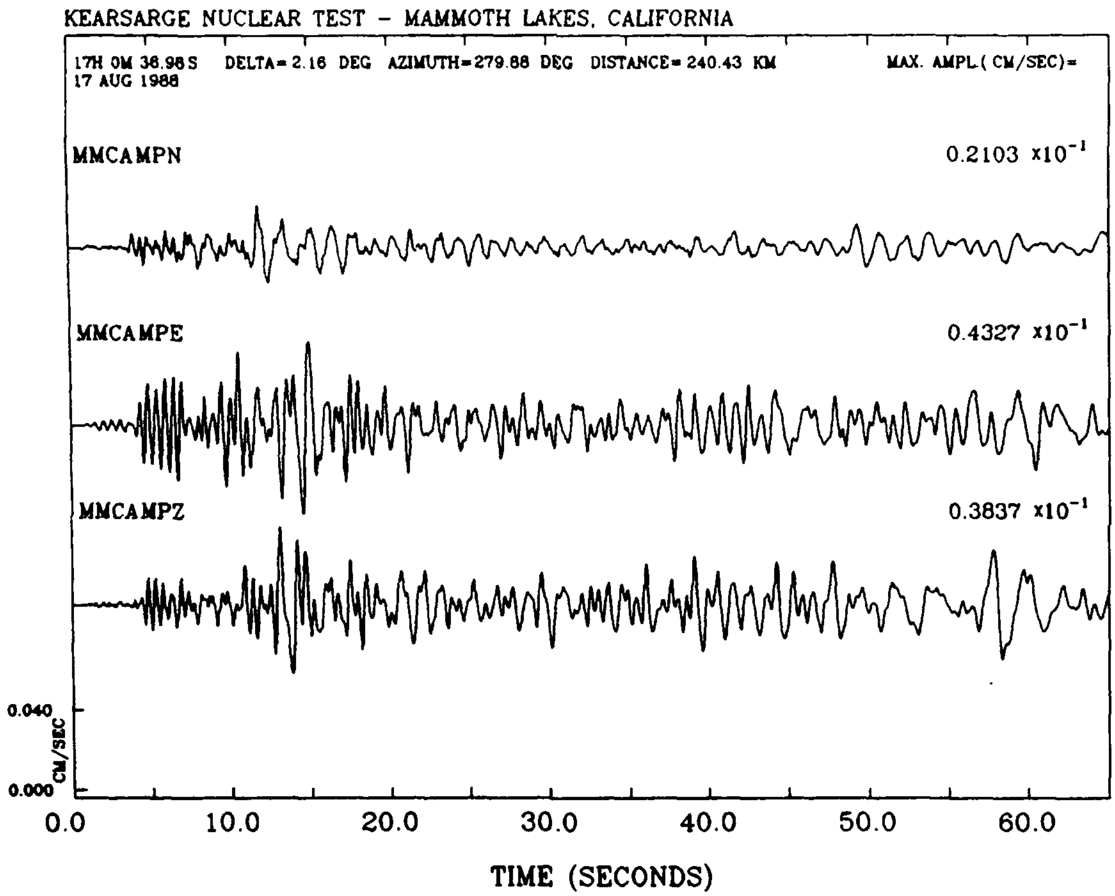


Figure 12. Sixty Seconds of the KEARSARGE Record at Mammoth Lakes. Each trace represents pendulum motion, uncorrected for instrument response. Absolute amplitude scale (shown at bottom left) in cm/sec is used. Distance, azimuth, and back azimuth are given at the top.

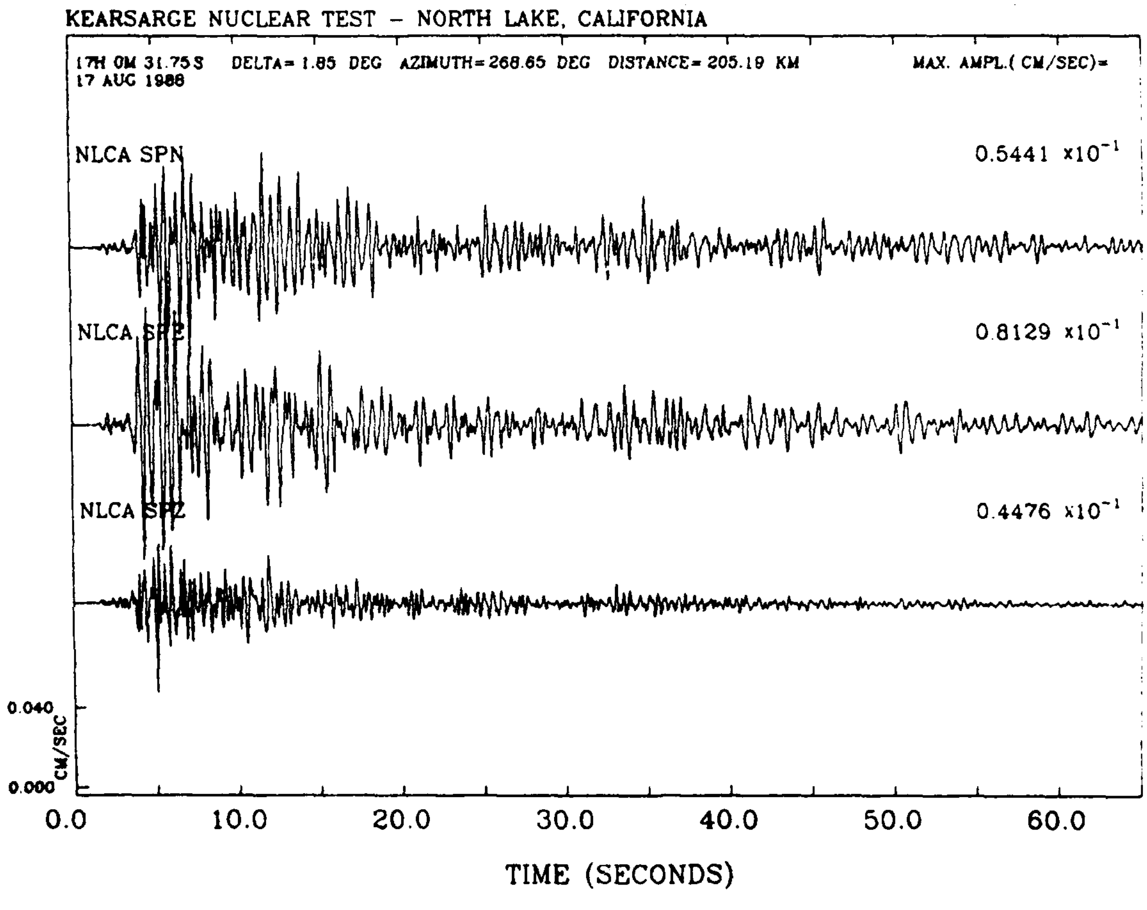


Figure 13. Sixty Seconds of the KEARSARGE Record at North Lake. Each trace represents pendulum motion, uncorrected for instrument response. Absolute amplitude scale (shown at bottom left) in cm/sec is used. Distance, azimuth, and back azimuth are given at the top.

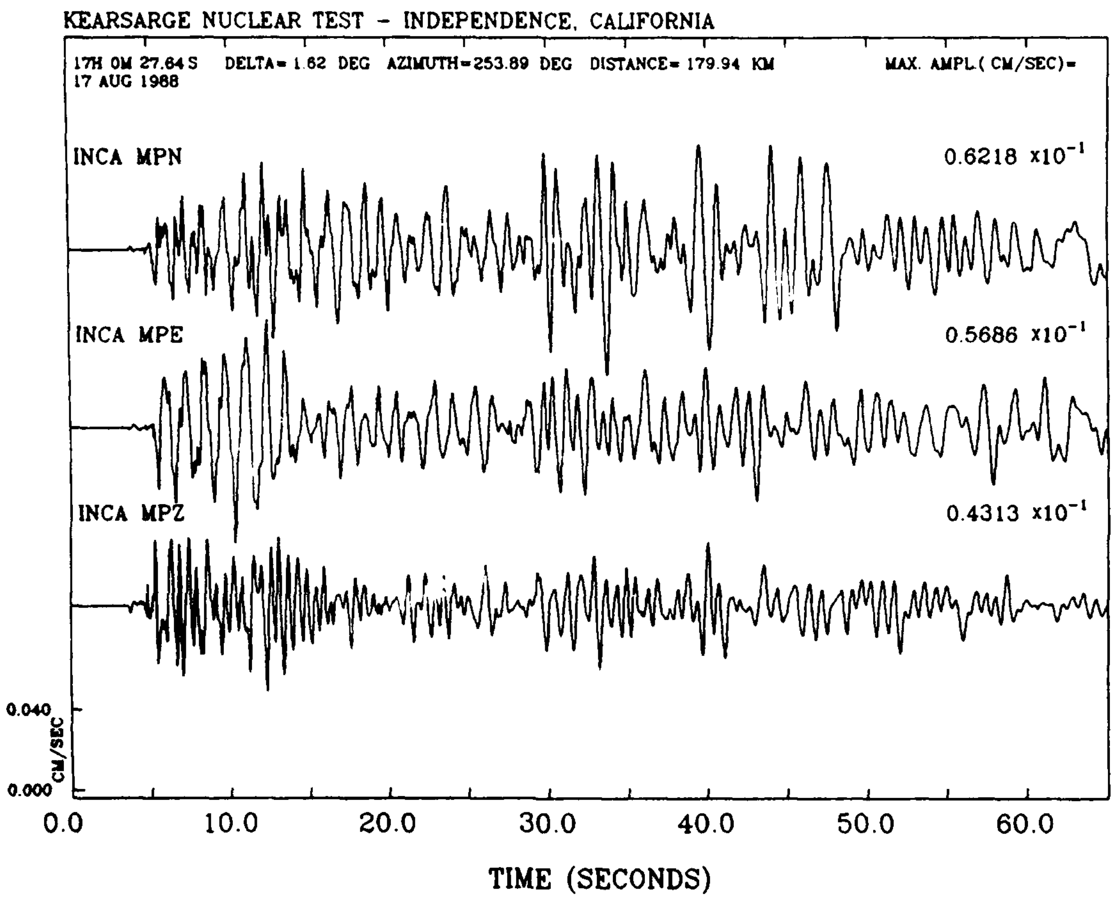


Figure 14. Sixty Seconds of the KEARSARGE Record at Independence. Each trace represents pendulum motion, uncorrected for instrument response. Absolute amplitude scale (shown at bottom left) in cm/sec is used. Distance, azimuth, and back azimuth are given at the top.

## 3. INTERPRETATION OF FIRST ARRIVAL TIMES

The boundary between the Sierra Nevada Mountains and the Basin and Range Provinces is as spectacular visually as it is important geologically. The mountains rise as much as 2-mi above the floor of Owens Valley along a complex series of faults, including the Owens Valley fault which broke in 1872 with an earthquake greater than magnitude 8. Owens Valley is a graben between the Sierras on the west and the Inyo-White Mountains to the east. Knowledge of the crustal structure in this area is critical to understanding the mode of uplift and deformation along this first-order tectonic boundary.[17,18,19]

The consensus of most geophysical studies is that a crustal root up to 55 km thick is present beneath the Sierra Nevada and that the crust thins eastward to 30-35 km in the Basin and Range.[9,10,20,11,12,8] Typical upper mantle P-wave velocities range between 7.8 and 8.0 km/sec.

The Pakiser and Brune[8] study is the one most relevant to Sierra structure. They model aftershock travel times from the 1966 Truckee, California, earthquake sequence recorded at stations deployed along the axis of the Sierra Nevada. Time delays at stations in the mountains relative to those outside suggest that the crust thickens from Truckee southward, reaching a depth of 55 km beneath Mount Whitney.

The alternative model, a rootless Sierra Nevada, was put forth by Carder et al[14] and Carder[15] based on travel time observations of several NTS explosions, as well as California earthquakes in the distance range 2-770 km. They conclude that the crust under the Sierra is thin with an anomalously low upper mantle P-wave velocity of 7.6 km/sec, and that the crust is thickened under the Inyo-White Mountains east of the Sierras. A portion of their NTS data set (triangles) is plotted along with the KEARSARGE data (circles) in Figure 15. The Carder et al[14] and KEARSARGE data sets are in excellent agreement where they overlap. Also shown is their best fitting straight line to the Pn observations over the entire data set. Note that the time delays observed at "Basin and Range" stations (150 to 250 km) are late, while the stations in the Sierra Nevada are early.

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[17] Chase, Clement G. and Wallace Terry C. (1986) Uplift of the Sierra Nevada of California, *Geology*, **14**, (No. 9):730-733.

[18] Chase, Clement G. and Wallace, Terry C. (1988) Flexural isostasy and uplift of the Sierra Nevada of California, *Jour. Geophys. Res.*, **93**, (No. B4):2795-2802.

[19] Crough, S. Thomas and Thompson, George A. (1977) Upper mantle origin of Sierra Nevada uplift, *Geology*, **5**, (No. 7):396-399.

[20] Mikumo, Takeshi (1965) Crustal structure in Central California in relation to the Sierra Nevada, *Bull. Seism. Soc. Am.*, **55**, (No. 1):65-83.

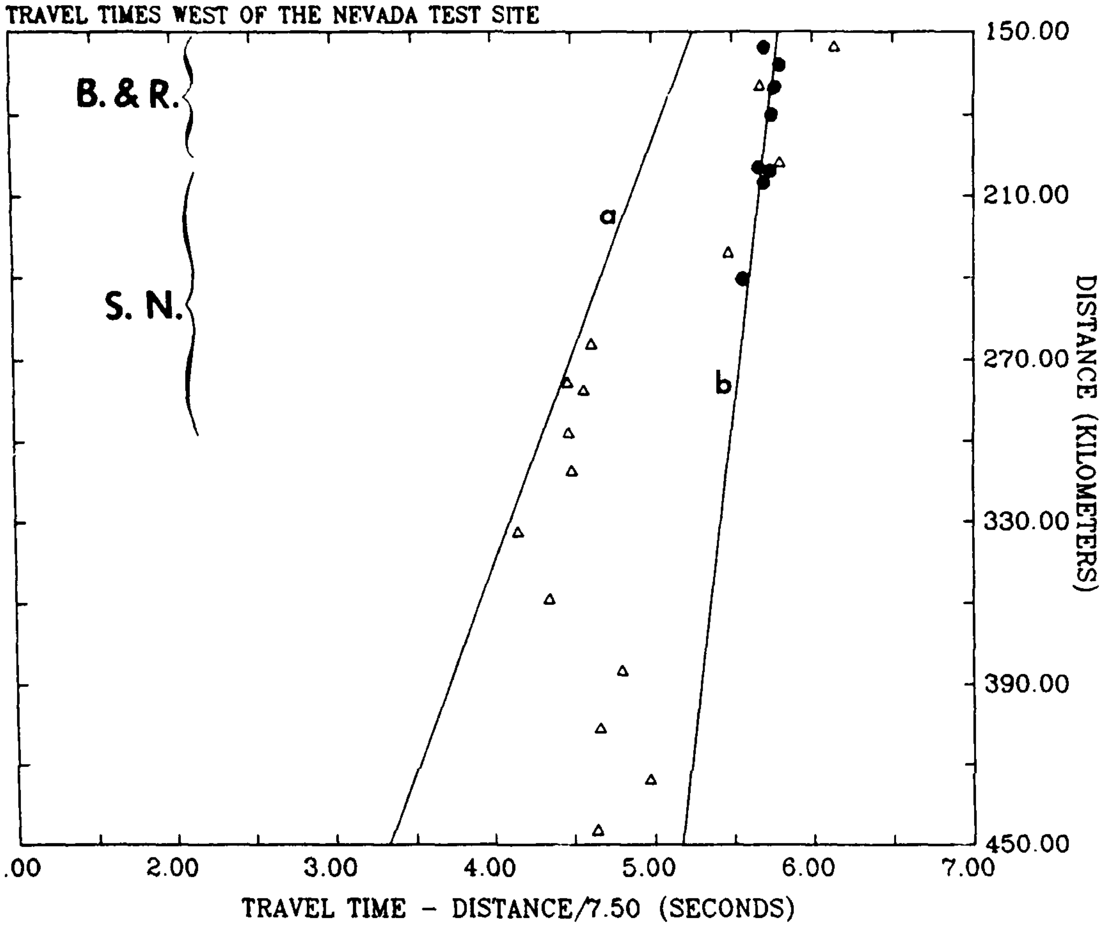


Figure 15. Travel Time Data from NTS. First arrival data of Carder et al (1970) and KEARSARGE (this study) are plotted as triangles and circles respectively. Line a is the Carder et al (1970) best-fitting straight line over the distance range 2 to 770 Km. Line b is the best-fitting line to the KEARSARGE data only.

An alternative explanation for the NTS data put forward by Pakiser and Brune[8] is that high velocity material rises upward under the Sierras and that the early Pn arrivals in the mountains are really refracted rays following this upward dipping layer.

The GL seismograms of KEARSARGE can be used for a preliminary interpretation of the structure of the Sierra Nevada-Basin and Range transition zone and to differentiate among the aforementioned crustal models. Figure 16 shows the vertical seismograms in record section format, at enlarged amplitude scale to emphasize the first arrivals. As expected for an event as large as KEARSARGE, the first arrivals have excellent signal to noise ratio. Circles indicate the picked arrival times (Table 4). Fitting a straight line to the data yields the travel-time equation:

$$T = 6.11 \text{ sec} + \text{Distance}/7.62 \tag{1}$$

with a standard error of 0.05-sec. Residuals are given in Table 4.

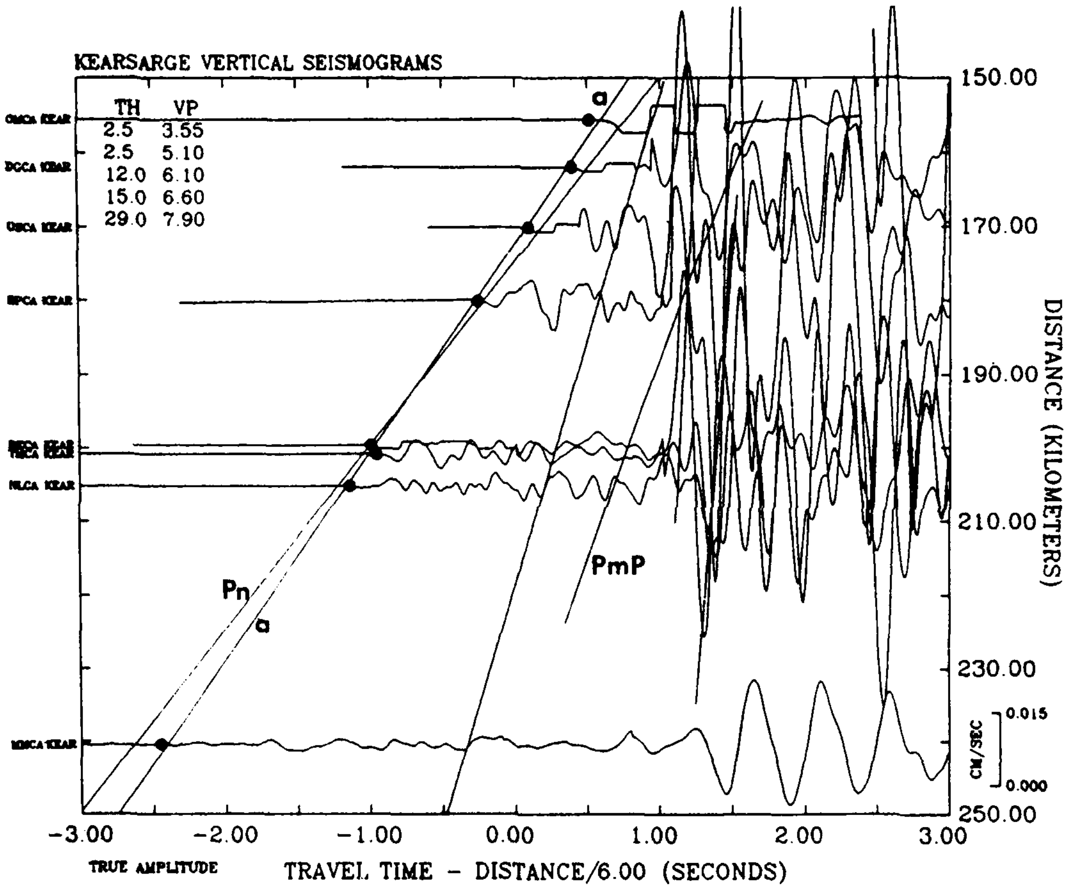


Figure 16. Vertical Records from KEARSARGE Plotted in Record Section Format Along with First Arrival Picks (circles). Line a is the best fitting straight line. Lines marked Pn and PmP are curves computed for model shown in upper left.

Table 4. KEARSARGE Travel Times and Residuals

| Station | Distance (km) | Travel Time (sec) | Observed- 6.105+D/7.619 (sec) | Observed- 6.22+D/7.88 (sec) |
|---|---|---|---|---|
| MMCA | 240.4 | 37.62 | -0.041 | 0.910 |
| NLCA | 205.2 | 33.06 | 0.022 | 0.820 |
| TMCA | 200.9 | 32.53 | 0.056 | 0.834 |
| BECA | 199.6 | 32.28 | -0.025 | 0.749 |
| BPCA | 180.1 | 29.76 | 0.021 | 0.709 |
| USCA | 170.1 | 28.45 | 0.016 | 0.661 |
| DGCA | 162.0 | 27.40 | 0.030 | 0.639 |
| OMCA | 155.6 | 26.45 | -0.079 | 0.502 |

Also shown on Figure 16 are travel-time curves for a modification of the Taylor[13] Pahute Mesa model where the upper three layers are lumped together and the Pn velocity is set at 7.9 km/sec. The KEARSARGE first arrival corresponds to the Pn branch, but at lower phase velocity. An attractive explanation for these data is that the true mantle P-wave velocity is the Basin and Range value, but that downward dip to the Moho produces the low apparent phase velocity of 7.62 km/sec. A simple model consisting of a single layer over a dipping halfspace was used to constrain the dip on the Moho. This model, shown in figure 17, has a flat Moho for 90 km west from the source where it begins to dip 3° downward. Crustal velocity is 6.1 km/sec based on the average of the Taylor[13] Pahute Mesa model. The crustal thickness is set at 32 km at NTS. Mantle velocity is assumed to be 7.9 km/sec. This simplified crustal model adequately accounts for the travel times observed in eastern California from KEARSARGE data and the Carder et al[14] Basin and Range data. It should be noted that there is a tradeoff between crustal thickness at the source and crustal velocity, so these parameters are not resolved. Assuming the Pn velocity, the Moho dip is well-resolved by this analysis.

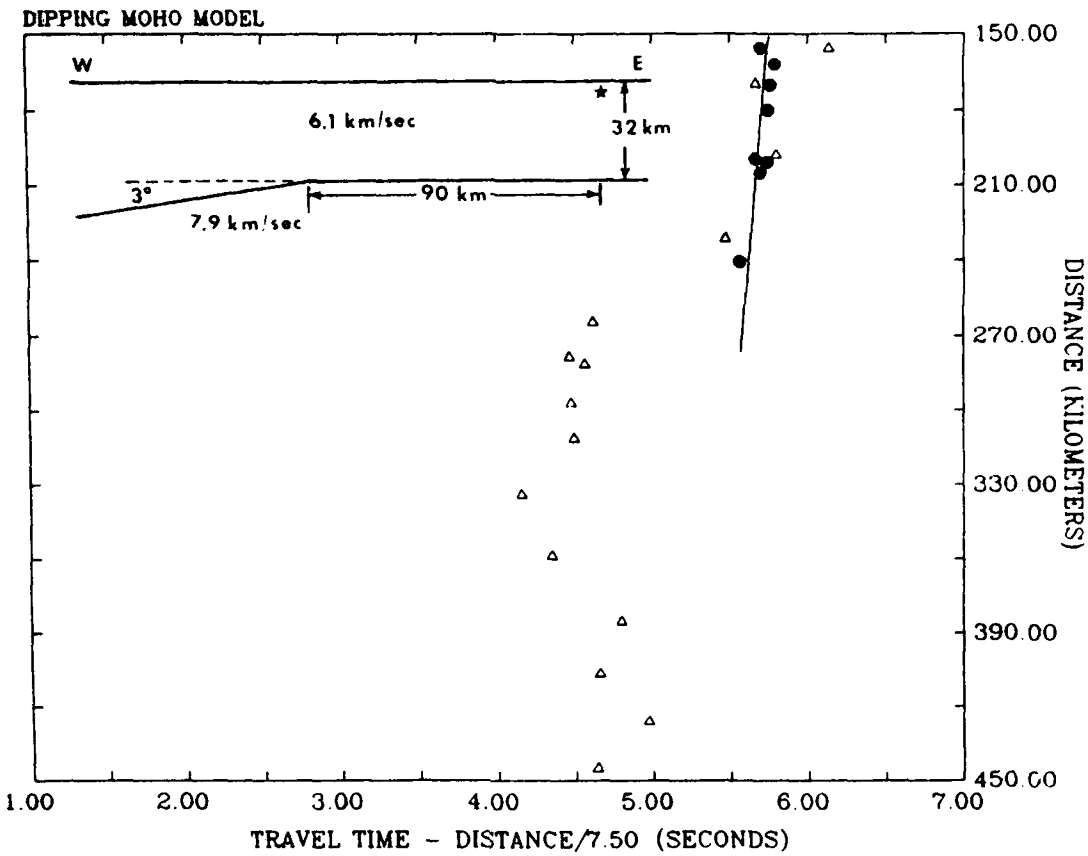


Figure 17. NTS Travel Times Compared to a Dipping MOHO Model (line a). Model is depicted schematically at the upper left.

## 4. CONCLUSIONS

A temporary ten-station seismic network was operated in eastern California to record the KEARSARGE nuclear test at the Nevada Test Site. Data from 8 three-component, short period stations and 2 three-component, mid-period stations are presented. Part of the array was arranged as a profile between 150 to 250 km from NTS. At these ranges, the first arrivals are Pn waves refracted along the crust-mantle boundary. The Pn travel times can be modeled by assuming a 32-km thick crust at NTS, which has a 3° westward dip beginning approximately 90 km west of the shot point. This model predicts a crustal thickness of 41.8 km at a point 277 km west of the shot point (that is, under the central Sierra Nevada). This model is in good agreement with Eaton[9] and Pakiser and Brune[8] and contrary to the model of Carder et al[14] and Carder[15]. There still remain significant offsets in the Carder et al[14] NTS travel-time data in the 250 to 270 km and 360 to 390 km distance ranges. Closely-spaced, digitally-recorded observations in those distance ranges are needed to completely resolve the seismic structure of the Sierra Nevada-Basin and Range transition zone.

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